Characteristics of Laser-Guided DC Discharge by Nd : YAG Laser at Low Pressure

Dong-Hoon Lee and Hee-Je Kim

Abstract

In recent years, concern has been raised about the technique of controlling electrical breakdown by using laser in many fields. Especially, laser has attracted much attention in the Electro-Discharge Machining(EDM) because of its many merits. Therefore, this research has been performed to obtain fundamental data relevant to discharge processing by using a pulsed Nd:YAG laser. The experiments of laser-guided dc discharge by laser radiation have been carried out at low air pressure ranging from 0.2 to 20 torr. The minimum laser-guided dc discharge voltage $V_{G.min}$ at the given pressures P and distances D between an anode and a cathode was measured. It is found that the minimum laser-guided dc discharge voltage is much lower than the natural discharge voltage V_{ND}, and the values of $V_{G.min}$ and V_{ND} as a function of $P \cdot D$ has a similar tendency. The laser output energy Eout decreases with input pulse duration tp increasing, and the more the value of tp increases, the higher that of $V_{G.min}$ is obtained because the number of photons during the discharge time N decreases with t_p increasing. There is the time lag frequently when the discharge by laser radiation is misguided under the condition of the applied voltage less than $V_{G.min}$.

I. Introduction

In recent years, concern has been raised about the technique of controlling electrical breakdown by using laser in many fields. For example, the studies on the switching of high current by a laser triggered discharge[1-2], the control of a discharge path by laser[3], laser-induced lighting[4-6], and a discharge process in use of laser[7] have been undertaken.

Especially, laser has attracted much attention in the Electro-Discharge Machining(EDM) because of its many merits[8]. For instance, although wire EDM[9] has became a fully competitive machining technique during the last decade, the process performance is limited by some typical restrictions : the risk of wire rupture and the bending of the wire. Wire rupture drastically reduces the overall efficiency of the EDM operation and wire deflection restricts the obtainable geometrical precision. But if laser were used in this kind of materials processing[10], many problems would be solved.

Pulsed Nd:YAG laser used in this experiment is the most commonly used type of solid-state lasers for many fields at present because of its good thermal and mechanical properties and easy maintenance[11]. In the recent studies of laser processing methods, the pulsed Nd:YAG laser which has various advantages over commonly used CO_2 laser has been investigated energetically; it can be focused on smaller point due to its short wavelength, and is smaller, cheaper, and more convenient in use compared to CO_2 laser.

To our knowledge, there have been few experimental data on this part in the country. Therefore, this research has been performed to obtain fundamental data relevant to materials processing by using a pulsed Nd:YAG laser.

In this paper, characteristics of laser-guided dc discharge by using a pulsed Nd:YAG laser radiation at low air pressure ranging from 0.2 to 20 torr have been investigated ; (1) effect of the distance and the pressure in the vacuum chamber, (2) that of the current pulse duration, and (3) time lags in laser-misguided discharge.

II. Experiments

A pulsed Nd:YAG laser, of our own designing and fabricating, was employed. The laser head contains a Nd:YAG rod, 76.2 mm in length and 6 mm in diameter. It was made by Union-Carbide. Nd:YAG host is a light violet crystal and neodymium concentration by atom percent in YAG has been limited 1.0-1.5%. Fluorescence from irradiated

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Xe flashlamp almost consists with absorbed spectral and lasing characteristics displayed by Nd:YAG. The flashlamp (model : ILC 6F3) is used to pump the laser rod.

The rear mirror has the concave curvature of 2 m. The front mirror is flat and has the reflectivity of 40 %. The laser output energy is variable, ranging up to about 1 J per pulse, with the stability less than 2%.

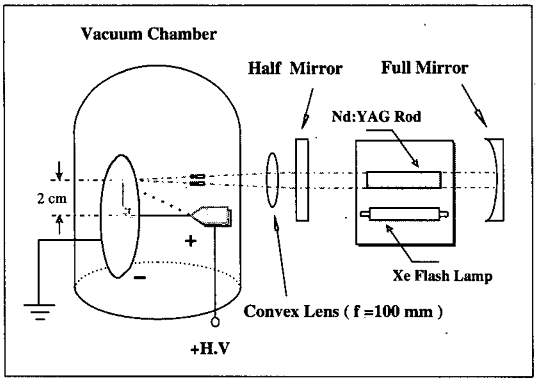

Fig. 1. Schematic view of experimental setup

The experimental arrangement is shown schematically in Fig. 1. The high voltage supply used in the experiment, of our own designing, consists of ten capacitors of 20 μF with the proof voltage of 1300 V, and is able to provide two electrodes with up to 6600 V. The vacuum chamber of 17.5 cm in diameter and 19 cm high was made of glass, so it is transparent. The stainless anode of 4 mm in diameter and 2 cm in length and the brass cathode of 7 cm in diameter and thickness of 2 mm were used. The power supply circuit employed in this study is shown in Fig. 2. It consists of 4 major components such as a rectifier, a charging power supply, a simmer circuit, a simmer starter.

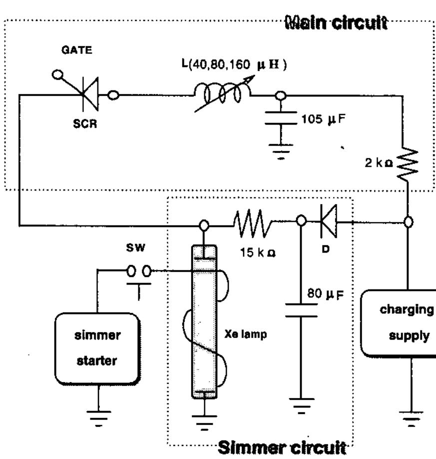

Fig. 2. Electric potential distribution obtained by FLUX2D at the electrode separation of 3cm

The simmer starter circuit creates an ionized spark streamer between two electrodes so that the main discharge can occur. The simmer starter voltage is about 8 kV, and its pulsewidth is about 3 μs. A 0.3 mm^2 nickel wire is wrapped around the flashlamp for easy triggering.

Before the main experiment was begun, we obtained a electric potential distribution between the electrodes by using the simulation program, called FLUX2D. Fig. 3 shows one of simulation results for the electrode separation of 3 cm. From the simulation results, it is estimated that natural discharge occurs from the edge of anode to the center of cathode.

In this study, in order to compare natural discharge with laser-guided discharge, a convex lens with 10 cm focal length was placed in front of the half mirror to focus laser beam the point, where was vertically 2 cm above from the center of cathode as shown in Fig. 1. The operational pressure P in the vacuum chamber was 0.2 to 20 torr, and the distance between two electrodes could be adjusted up to 7 cm. The experimental procedures was as follows. (1) The electrode distance D and the operational pressure P were adjusted. (2) DC high voltage was applied in the electrodes. (3) We measured the Natural Discharge Voltage V_{ND} as a function of P and D. (4) Laser beam was injected on the point of cathode as reducing the applied voltage, and then we investigated that the discharge was guided to it or not. (5) We measured the Minimum Laser-Guided DC Discharge $V_{G.min}$.

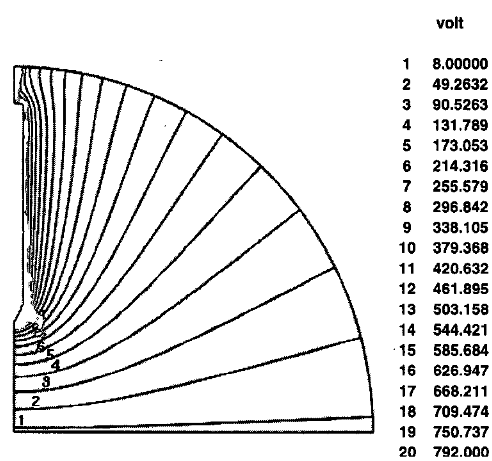

Fig. 3. Power supply circuit of Pulsed Nd:YAG laser

III. Results and Discussion

1. Effect of the distance and the pressure

The data shown in Fig. 2 were obtained in accordance with the distance D between the cathode and the anode for each case of 0.3 and 5 torr. Here, laser output energy E_{out} was 300 mJ. As can be seen from this figure, $V_{G.min}$ at 0.3 torr is nearly independent on the distance D, but $V_{G.min}$ at 5 torr broadly changes according to D ; the former ranges from 135 to 190 V, and the latter from 350 to 680 V. $V_{G.min}$ at 5 torr broadly changes according to D ; the former ranges from 135 to 190 V, and the latter from 350 to 680 V.

Fig. 4 shows the data measured by varying the pressure P in vacuum chamber (0.5, 1, 5, and 10 torr) at D = 3 cm. At P = 0.5 and 1 torr (region A), $V_{G.min}$ is just about 30 % of V_{ND} ; V_{ND} is 615 V and $V_{G.min}$ is 195 V at 0.5 torr, and V_{ND} is 625 V and $V_{G.min}$ is 220 V at 1 torr. At P = 5 and 10 torr (region B), $V_{G.min}$ is about 60 % of V_{ND} ; V_{ND} is 870 V and $V_{G.min}$ is 480 V at 5 torr, and V_{ND} is 1160 V and $V_{G.min}$ is 750 V at 10 torr.

According to the researches on the electrical breakdown by laser radiation[12,13], the air gap length and the density of laser-produced plasma enough to induce an electron avalanche is required for the breakdown. It presents that the Minimum Laser-Guided DC Discharge $V_{G.min}$ is dependent on the air pressure P in a vacuum chamber, the electrode separation D and the number of laser-produced electrons.

As a result, it is found that the values of $V_{G.min}$ and V_{ND} as a function of P·D has a similar tendency : $V_{G.min}$ and V_{ND} increase gradually up to about P·D = 5 torr·cm, which they increase abruptly. In addition, The experimental range of Fig. 2(a) is near the Paschen minimum, which is known as about 0.5 (torr·cm)[14], and the values of P·D in Fig 2(b) and Fig. 3 is much larger than it.

2. *Effect of the current pulse duration*

As it is mentioned above, the number of laser-produced plasma is regarded as a significant factor in laser-guided discharge. So we investigated the influence of different laser beam profiles, providing a photon energy with the electrons in the cathode surface, on laser-guided discharge.

In this study, in order to generate the laser beams, the current pulse duration of flashlamp t_p was chosen as a variable, and it was adjusted by inductance L shown in Fig. 2[11].

Fig. 4 shows the current waveforms through two electrodes during the discharge time, the current waveforms applied to the flashlamp and laser output profiles at D = 2 cm, P = 0.3 torr and laser output E_{out} = 185 mJ. The current waveforms were measured by a pulsed current transformer (Pearson Electronics Co. Ltd.) and a digital storage oscilloscope (Lecroy 9310AM, 400 MHz).

Table 1 shows the values of t_p and laser output energy E_{out} corresponding to different L of 40, 80, and 160 μH, V_{ND}, $V_{G.min}$ and N, which is the number of photons emitted from the laser during discharge time of about 40 μs. From this results, we found that the values of E_{out} decreased with increasing inductance L. Therefore, the power supply voltage of the Nd:YAG laser was needed to be adjusted so that we could investigate the effect of not the reduction of laser output energy E_{out} as a function of L but the current pulse duration t_p on $V_{G.min}$.

Table 1. The values of t_p, E_{out}, V_{ND}, $V_{G.min}$, and N corresponding to different L of 40, 80, and 160 μH

	t_p(μs)	E_{out}(mJ)	V_{ND}(V)	$V_{G.min}$(V)	N (E_{out}=185mJ)
L= 40 μH	160	210~215	485~500	160~170	3.01×10^{17}
L= 80 μH	210	200~205	485~500	185~195	2.50×10^{17}
L=160 μH	300	180~185	485~500	215~220	2.08×10^{17}

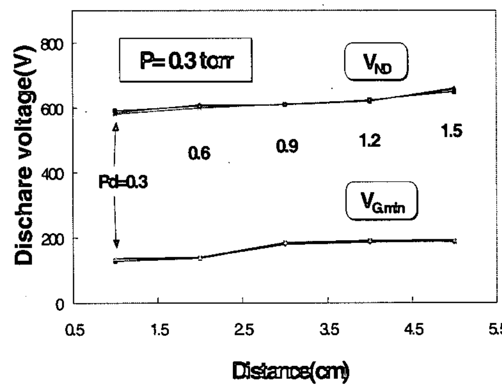

Fig. 4(a)

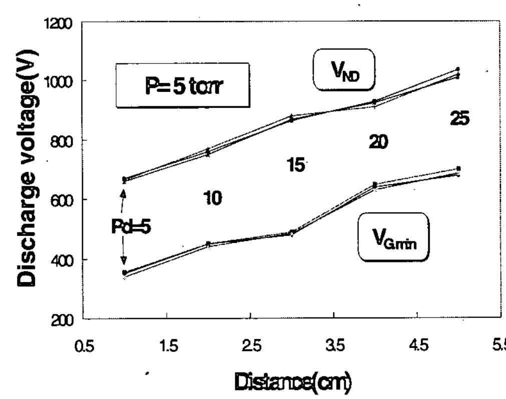

Fig. 4(b)

Fig. 4. Effect of the distance on laser guided discharge (a) at P = 0.3 torr and (b) at P = 5 torr when laser output E_{out} is 300 mJ

In Fig. 4, the value of area (c) indicates the ratio of time-integrated photon's quantity to total one during the discharge time of about 40 μs. And the reason why we calculate N is that the photons from laser within 40 μs only influence on discharge. N can be obtained by the following formula

$$N = \frac{E_{out}}{h\nu} \times \alpha \tag{1}$$

where h is Planck's constant, ν is the frequency of Nd:YAG laser, and α is the proportion of area (c) to total area 40.8435 (μVs) of laser output profile in Fig. 4.

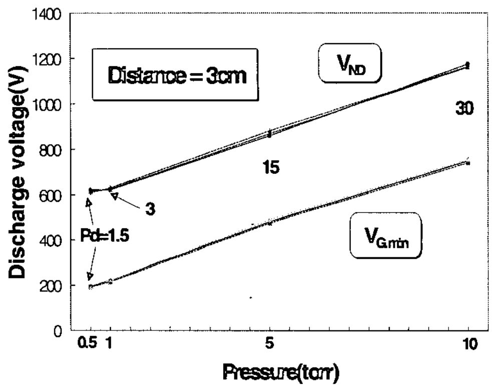

Fig. 5. Effect of the pressure on laser-guided discharge at D = 3 cm when laser output E_{out} is 300 mJ

The values of α corresponding to different L of 40, 80, and 160 μH are 0.30, 0.25, and 0.21, respectively. Therefore, it is considered that more photons injected to the cathode during the discharge time can induce discharge at lower voltage.

As a result, the important findings in this experiment are ; (1) laser output energy E_{out} decreases with increasing inductance L (2) the minimum laser-guided discharge voltage $V_{G.min}$ increases as inductance L increases because the number of photons during the discharge time N decreases with L increasing.

3. Time lags in laser-misguided discharge

In this section, we compared laser-guided discharge with laser-misguided discharge, which is induced to the not-focused points, as the applied voltage between electrodes. The condition of this experiment was P = 5 torr, D = 2 cm, L = 90 μH and E_{out} = 185 mJ.

Fig. 6(a) shows the current waveform and the laser beam profile in the case of laser-guided discharge when the input voltage of 450 V, which is higher than $V_{G.min}$ (420 V) at the above condition, is applied in the electrodes. Fig. 6(b) demonstrates the discharge current laggs about 60 μs behind the laser beam when the discharge by laser radiation is not guided the laser-injected point at the case of appling 400 V lower than $V_{G.min}$ (420 V).

The experimental condition of Fig. 6(a) and Fig. 6(b) was same except the applied voltage in electrodes. It means that the density of neutral atoms, the mean free path and the number of laser-produced plasma are same, whereas the magnitude of the electric field in Fig. 6(b) is small compared with that of the electric field in Fig. 6(a).

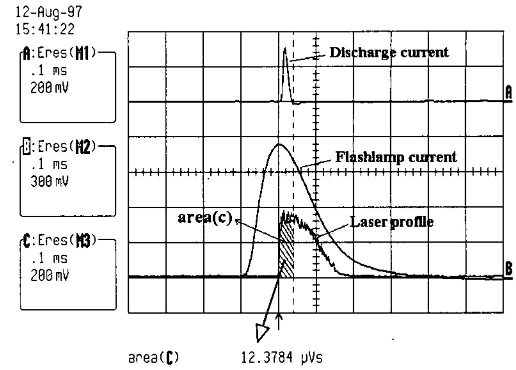

Fig. 6(a)

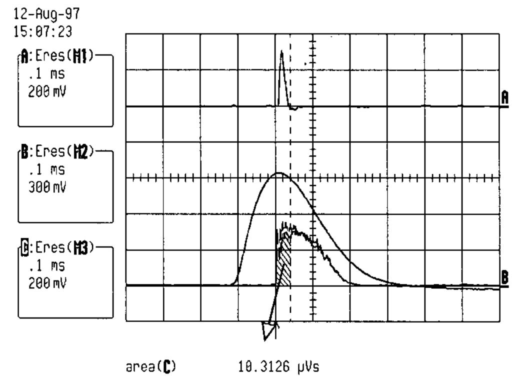

Fig. 6(b)

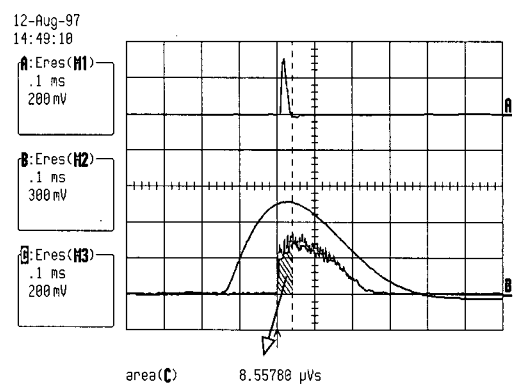

Fig. 6(c)

Fig. 6. Effect of the current pulse duration on laser guided discharge (a) at L=40 μH, (b) at L=80 μH, and (c) at L=160 μH when laser output Eout is fixed at 185 mJ

The kinetic energy E_k and the drift velocity v_d of a particle are

$$E_k = \frac{1}{2} m v_d^2 \ [eV] \quad (2)$$

$$v_d = \mu E \ [m/\sec] \quad (3)$$

where m is the mass of a particle, μ is the mobility of a particle, and E is the electric field applied in the electrodes.

As we know, primary electrons and secondary electrons must have the kinetic energy enough to ionize neutral atoms for the electron avalanche. Therefore, in the case of Fig. 6(b), it takes more time that E_k of laser-produced electrons reaches up to ionization energy because the electric field E is lower than $V_{G.min}$ / D, which is considered as the minimum electric field for laser-guided discharge.

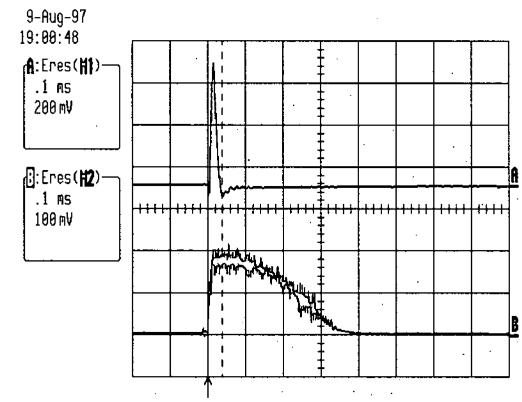

Fig. 7(a)

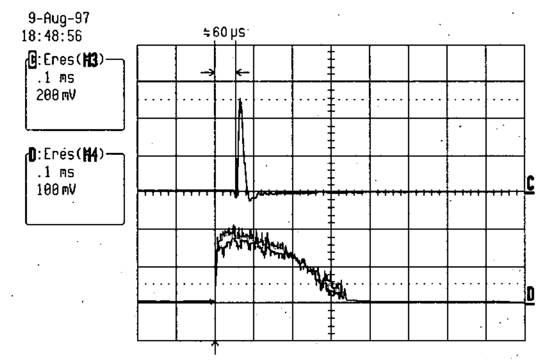

Fig. 7(b)

Fig. 7. Comparision of laser-guided discharge and laser-misguided discharge in time lags as applied voltage between the electrodes at P = 5 torr, D = 2 cm, L = 90 μH, and E_{out} = 185 mJ

IV. Conclusion

As a fundamental research to be applied to the Electro-Discharge Machining(EDM), the experiment of laser-guided dc discharge by the pulsed Nd:YAG laser has been carried out at low pressure ranging from 0.2 to 20 torr. From this study, the obtained major results are as follows.

1. The minimum laser-guided dc discharge voltage $V_{G.min}$ and V_{ND} as a function of P·D has a similar tendency : $V_{G.min}$ and V_{ND} increase gradually up to about P·D = 5 torr·cm, which they increase abruptly.

2. The laser output energy E_{out} decreases with input pulse duration t_p increasing. And the more the value of t_p increases, the higher that of $V_{G.min}$ is obtained because the number of photons during the discharge time N decreases with t_p increasing.

3. There is a time lag when the discharge by laser radiation is misguided, in the case that the voltage less than $V_{G.min}$ is applied in the electrodes.

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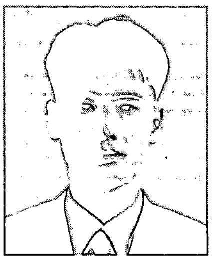

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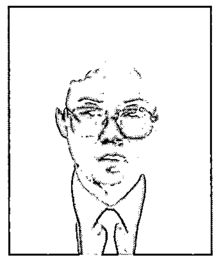

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